Simulation of Water Supply and Demand in the Aral Sea Region

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ABSTRACT

The Aral Sea, a huge saline lake located in the arid south-central region of the former U.S.S.R., is vanishing because the inflows from its two feed rivers, the Amudar'ya and Syrdar'ya, have diminished radically over the past three decades. The loss of river flow is the result of massive increases in river withdrawals, primarily for cotton irrigation in the basins. A microcomputer model, the Water Evaluation and Planning System (WEAP), has been developed for simulating current water balances and evaluating water management strategies in the Aral Sea region. WEAP treats water demand and supply issues in a comprehensive and integrated fashion. The scenario approach allows flexible representation of the consequences of alternative development patterns and supply dynamics. For the Aral region's complex water systems, a detailed water demand and supply simulation was performed for the 1987-2020 period, assuming that the current practices continue. The analysis provides a picture of an unfolding and deepening crisis. Policy scenarios incorporating remedial actions will be reported in a separate paper

INTRODUCTION

The Aral Sea, a saline lake located in the arid south-central region of the former U.S.S.R. is vanishing (Fig. 1). Once the fourth largest lake in the world by area, the Aral Sea today is nearing half of its surface area in 1960, less than one-third its previous size by volume. If current patterns continue, the lake will diminish to several residual lifeless brine lakes next century.

The Aral is shrinking because the flows from its two feed rivers, the Amudar'ya and Syrdar'ya, have decreased from over 50 km^3 per year thirty years ago to a mere trickle. The loss of river flow is the result of massive increases in river withdrawals, primarily for irrigation, along the river basins. The two rivers begin at the Pamir and Tianshan plateaus, plunge downward into the desert of the Central Asian republics and terminate at the Aral Sea. Since the 1960s an immense system of dams and reservoirs has been developed in the region. Today, the Aral basin is an astonishingly complex web of canals, impoundments, irrigation fields, and water engineering facilities. The waters in the two rivers are the lifeblood of the agricultural economies in five Central Asian republics of the former U.S.S.R.: Turkmen, Uzbek, Tadzhik, Kirgiz, and Kazakh, supporting 7.6 million hectares of irrigated crops. The current patterns of water use and the recession of the lake has generated multiple environmental and economic problems [l-5]. The scale of these problems is substantial, covering an area of 3.5 million km^2 and affecting some 35 million inhabitants in the five republics. There is an international consensus that the situation is not ecologically sustainable and comprehensive strategies for altering water development patterns are needed.

Beyond the deterioration of the lake and the loss of its fishing industry, there are other serious impacts. For example, the recession of the sea has created a huge area — about 30,000 km^2 — of salt on the former lake bed, Toxic to humans and deleterious to crops, the salt is whipped up by winds and carried over wide areas. The ecology of the river deltas has been seriously degraded as the surrounding water

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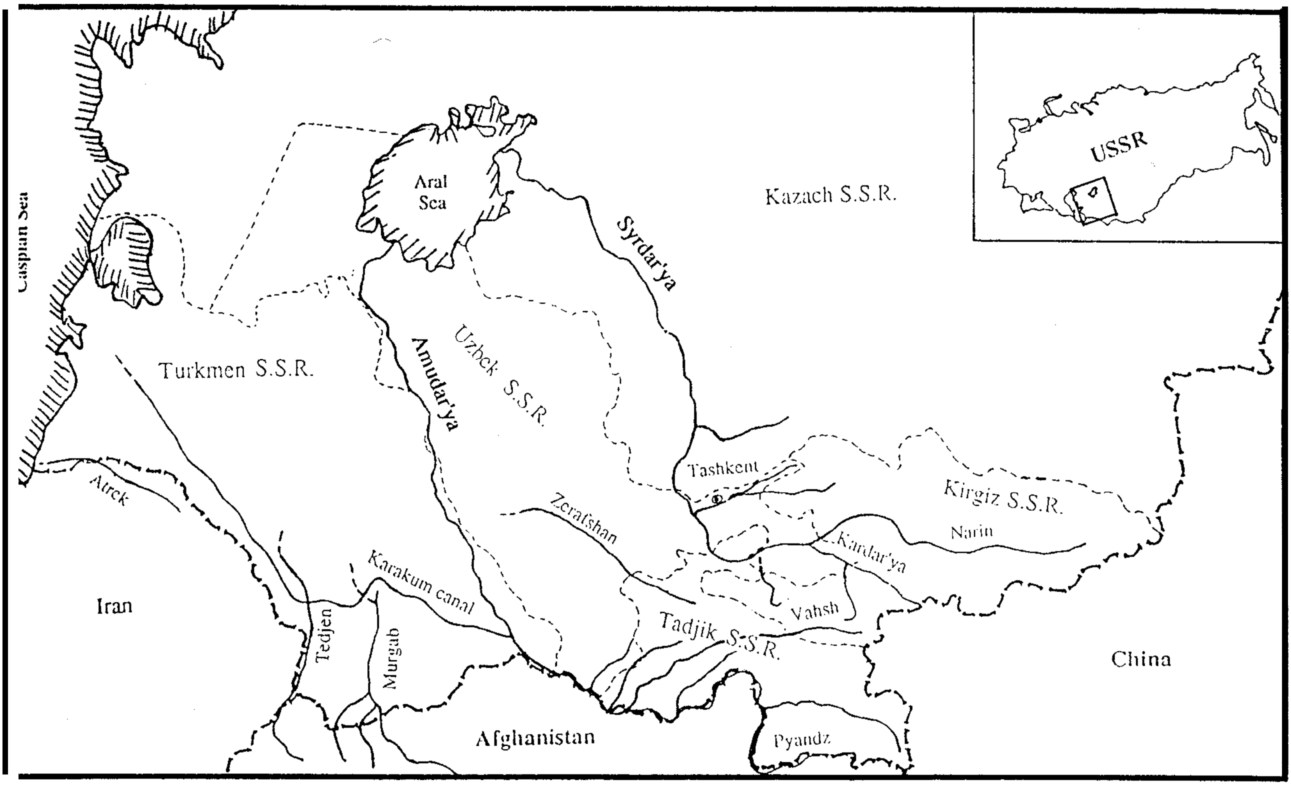

Figure 1. A map of the Aral Sea Region.

table falls along with the sea, and river flow diminishes. In addition, regional climate may be changing as the modulating influence of the Aral diminishes with its size, with summers and winters apparently becoming more severe [2]. Shorter growing seasons, compounded by soil salinization and salt storm deposits, would expand water shortages by further increasing the requirements for water. Last, but not least, there is great concern that deteriorating water quality will lead to a deepening public health crisis.

Regional climate may be changing as the modulating influence of the Aral diminishes

A microcomputer model, the *Water Evaluation and Planning System* (WEAP), was developed for evaluating alternative water development policy options in complex systems such as the Aral Sea region [6]. Employing the scenario approach, the WEAP model provides a structured approach to integrated water demand-supply analysis.

This paper presents results of a "business-as-usual" simulation of the region's water supply for the 1987-2020 period, assuming that the current practices continue. Development and evaluation of alternative water policy scenarios will be reported in future papers. In this paper, we focus on illustrating the magnitude of the problem and the challenge for devising sustainable water strategies for the Aral region.

CURRENT WATER DEMAND AND SUPPLY

Comprising lowland deserts and mountains, the Aral region has a climate characterized by high evapotranspiration and severely arid conditions. Annual precipitation is less than 100 mm in the southwest deserts and about 200 mm approaching the foothills of the southeastern mountains. However, the region has favorable thermal conditions for the growth of cotton and other heat-loving crops: the average noontime temperature during growing seasons (May-September) reaches 20-45°C and the average daily temperature in July is 35°C [7]. Although thin and infertile, soil in the region is easily tilled and productive for certain crops with the application of supplementary water. These favorable conditions have provided the natural base for intensive irrigated agricultural development, particularly the large scale production of cotton in the Aral region.

The Amudar'ya and Syrdar'ya basins have some 30 primary tributaries (Figs. 2 and 3). More than 20

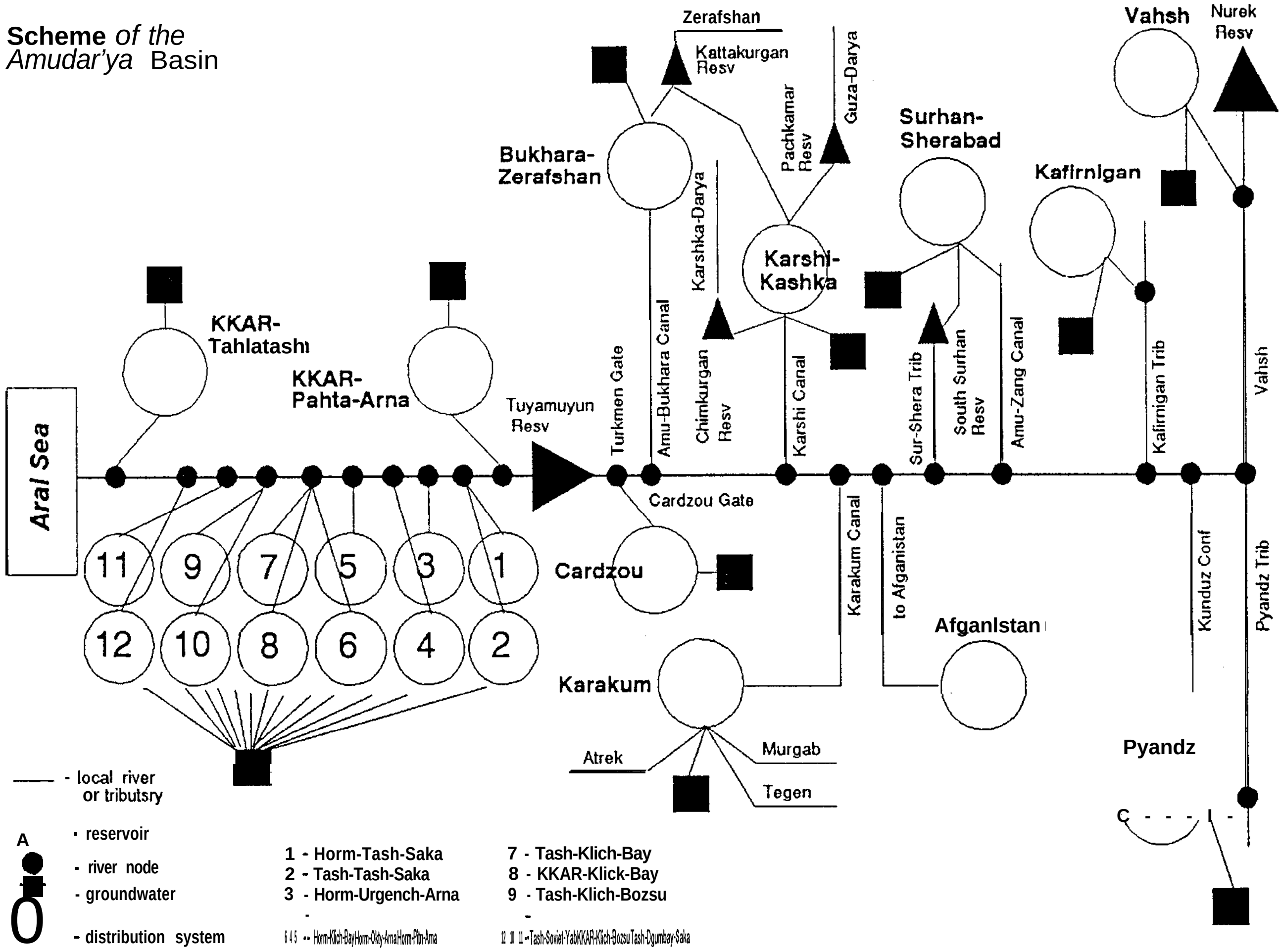

Figure 2. Scheme of the Amudar'ya Basin.

One of the most complicated human water development systems in the world

large and middle sized reservoirs and 60 canals of different sizes have been constructed in the two basins since the 1950s [8-l0]. The Karakum canal, constructed in 1950s as a centerpiece of Soviet plans to expand cotton production, diverts water from Amudar'ya with a maximum flow of 320 m^3 per second over 840 kilometers to the vast Karakum desert. In addition, approximately ten per cent of supplies are from groundwater sources. The region's water system is one of the most complicated human water development systems in the world.

In designing the-schematic representation of the two basins, we have aimed for as much detail as possible in characterizing both demand and supply sources, subject to the availability of field data. Referring to Figs. 2 and 3, the representations consist of the following main elements:

- *Distribution Systems* A distribution system represents water users in a common geographic area with shared water sources. In the current representation, distribution systems are identified with "irrigation systems" that are used for allocating water in the Aral ,region. There are 23 distribution systems identified for Amudar'ya, and 6 for Syrdar'ya. Irrigation systems at the lower Amudar'ya area are further separated into twelve districts (indicated by the naming convention "administrative district/irrigation system," e.g., Horezm/ Tash-Saka). Water demand in each distribution system is subdivided by major sectors: irrigation (further partitioned by crop type and irrigation technique), industry (by type), municipal (by urban and rural), fishery, and livestock.
- *Main River and Tributaries* These are the primary water conduits in the region. Stream flows are estimated along every tributary and the main rivers on a monthly basis. Account is taken of inflows, outflows, withdrawals, evaporative losses, and groundwater interactions. There are five types of river nodes: *reservoir node, withdrawal node, diversion* ***node, confluence node*** and *tributary node.*

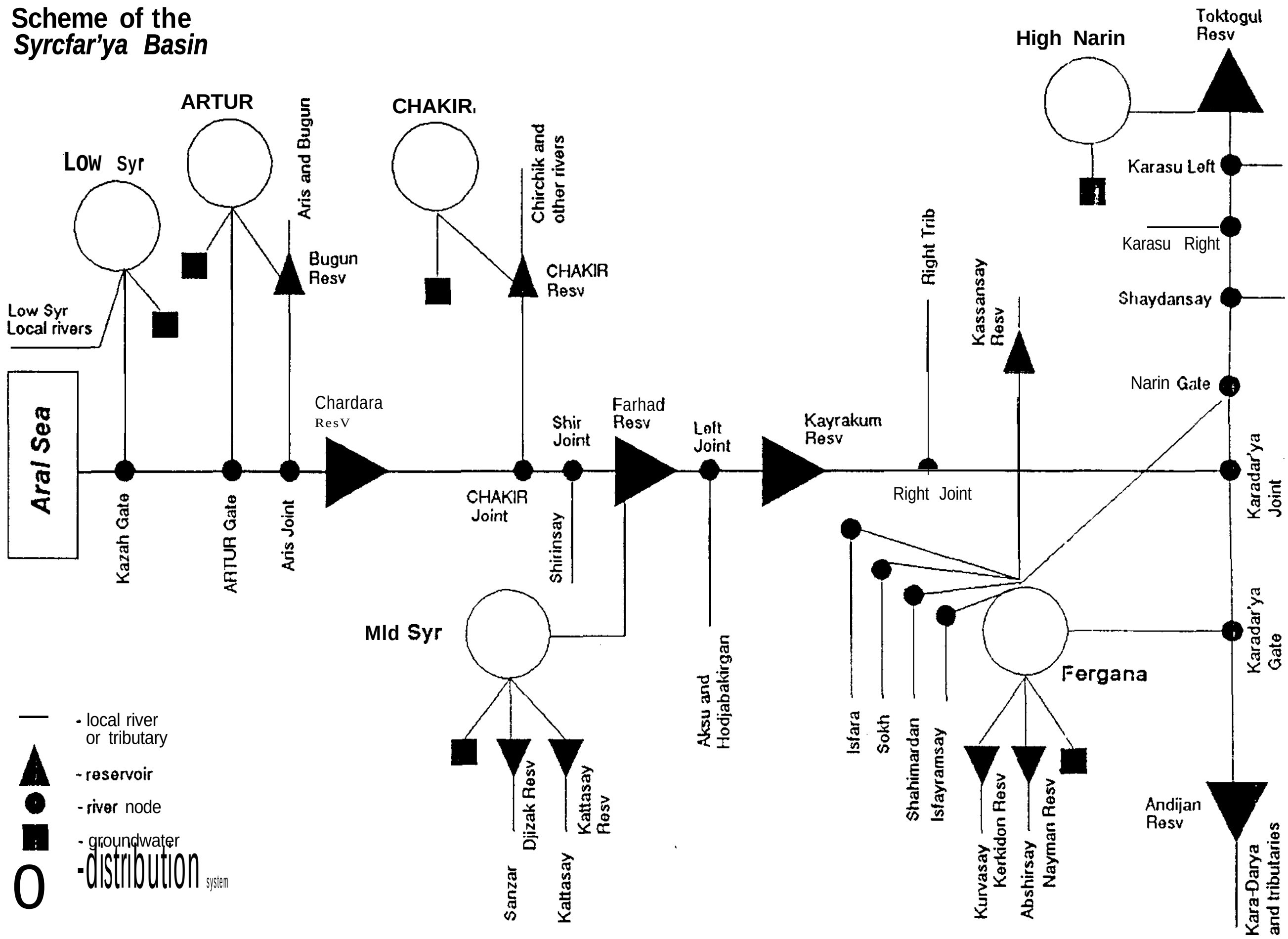

Figure 3. Scheme of the Syrdar'ya Basin.

Each is simulated according to its operating rule. For instance, WEAP's reservoir operating rule takes into account a reservoir's inflow, storage capacity, surface evaporation, withdrawal at the reservoir, hydroelectric generation, and downstream release requirements. In-stream flow requirements for maintaining, for example, environmental quality also may be specified.

- *Local Supply Sources* These include run-of-river pumping stations, groundwater aquifers, rainwater collection, and reservoirs on rivers that are hydrologically independent of the main river system. In WEAP, withdrawal demands are met by local sources with residual requirements assigned to any river linkages.
- *Links between Distribution Systems and Supply Sources* Transmission links between demand sites and supply sources are identified in the system representation. Each distribution system may be supplied by a maximum of twelve sources with links to ten "local" sources, one tributary node and one main river node. Capacity constraints and conduit losses are taken into account.

1987 Water Demand

Water accounts have been estimated for the year 1987, the most recent year for which comprehensive data is available. Water demands for that year are summarized in Table 1, broken down by each sector for each distribution system. The total water demand for the Aral region is 97.32 km^3. Of this total, 53.55 km^3 is demanded from the Amudar'ya basin, and 43.77 km^3 from the Syrdar'ya basin. Water demands are dominated by the agriculture sector, accounting for 82 per cent of the total demand.

The region's irrigated areas by type of crop are summarized in Table 2 [11]. The total irrigated area of the region in 1987 was 7.6 million hectares, with 4.3 million hectares located in the Amudar'ya basin, and 3.3 million hectares in the Syrdar'ya basin. Water demand shares by crop types in the two basins are presented in Fig. 4. Cotton is the major crop, accounting for 51 per cent of the agricultural water demand in Amudar'ya, and 34 per cent in Syrdar'ya. The Soviet Union has been the second largest cotton producer in the world, producing over 90 per cent of its fiber in the Aral region. Clearly, strategies for

Table 1. 1987 Water Demand of the Aral Region (Unit: km^3).

Distribution System	Agriculture	Industry	Municipal	Livestock	Fishery	Total
Amudar'ya Basin						
Pyandz	1.11	0.05	0.22	0.02	0.02	1.42
Vahsh	2.48	0.08	0.30	0.03	0.19	3.08
Kafirnigan	1.40	0.03	0.25	0.01	0.45	2.14
Surh-Sherabad	3.19	0.00	0.27	0.01	0.03	3.50
Afghanistan	0.00	0.00	0.00	0.00	0.00	0.00
Karakum	7.22	1.69	0.41	0.02	0.07	9.41
Kashkadraya	5.56	0.05	0.40	0.01	0.05	6.07
Bukhara-Zerafshan	8.89	0.66	0.65	0.11	0.04	10.35
Cardzou	2.39	0.17	0.16	0.00	0.09	2.81
Horezm	2.60	0.05	0.15	0.00	0.05	2.85
Tashaus	2.59	0.00	0.05	0.00	0.05	2.69
KKAR	7.37	0.20	0.12	0.03	1.51	9.23
Amu Total	44.80	2.98	2.98	0.24	2.55	53.55
Percentage	84	6	6	0	5	100
Syrdar'ya Basin						
High Narin	2.11	0.01	0.03	0.00	0.07	2.22
Fergana Valley	12.48	0.31	1.31	0.00	0.07	14.17
Middle Syrdar'ya	7.45	2.14	0.33	0.00	0.12	10.04
CHAKIR	5.17	2.30	1.39	0.00	0.12	8.98
ARTUR	2.11	0.21	0.15	0.00	0.12	2.59
Lower Syrdar'ya	5.26	0.07	0.11	0.00	0.33	5.77
Syr Total	34.58	5.04	3.32	0.00	0.83	43.77
Percentage	79	12	8	0	2	100
Aral Total	79.38	8.02	6.30	0.24	3.38	97.32
Percentage	82	8	6	0	3	100

Note: percentage *figures may not total correctly, due to rounding.*

Table 2. 1987 Irrigation Areas (Unit: 1,000 hectares).

	Cotton	Rice	Wheat	Maize	Cereals	Potato	Veg.	Melon	Fodder	Vineyd.	Orchard	Total
Amudar'ya Basin												
Pyandz	55.0	1.5	1.9	1.9	1.9	1.9	3.7	1.7	29.6	5.3	11.7	116.0
Vahsh	123.2	3.4	4.2	4.2	4.2	4.3	8.3	3.9	66.3	11.8	26.3	260.0
Kafimigan	61.6	1.7	2.1	2.1	2.1	2.1	4.1	2.0	33.2	5.9	13.1	130.0
Surh-Sherabad	199.3	8.5	12.3	6.9	6.1	2.9	7.4	3.3	74.4	15.7	24.2	361.0
Kashkadraya	310.5	0.1	28.0	9.7	18.1	4.1	13.7	8.1	129.7	30.9	32.1	585.0
Bukhara-Zerafshan	443.9	20.1	18.1	18.0	11.9	5.1	17.7	10.9	184.2	37.1	44.0	811.0
Cardzou	175.4	0.0	17.5	11.1	0.0	1.1	7.8	11.4	0.0	8.7	8.1	241.0
Karakum	507.2	0.0	50.5	32.1	0.0	3.2	22.4	32.9	0.0	25.3	23.4	697.0
Horezm	120.6	29:0	1.7	2.4	0.5	0.9	4.4	4.9	55.8	1.3	9.1	230.5
Tashaus	208.7	0.0	20.8	13.2	0.0	1.3	9.2	13.5	0.0	10.4	9.6	286.8
KKAR	237.7	125.7	0.9	14.9	0.9	2.0	6.8	11.2	173.6	1.2	13.8	588.6
Amu Total	2443.1	190.0	157.9	116.4	45.7	28.9	105.6	103.8	746.7	153.6	215.4	4307.0
Percentage	57	4	4	3	1	1	2	2	17	4	5	100
Syrdar'ya Basin												
High Narin	82.0	2.3	2.8	2.8	2.8	2.8	5.5	2.6	44.1	7.9	17.5	173.1
Fergana Valley	787.6	10.9	31.8	40.3	23.2	11.2	32.6	12.6	272.8	38.8	103.9	1365.6
Middle Syrdar'ya	288.5	54.4	17.5	23.5	11.8	4.0	11.0	10.7	207.4	20.7	30.9	680.4
CHAKIR	142.9	49.3	10.8	15.9	5.3	6.3	16.2	7.0	162.3	14.3	32.4	462.7
ARTUR	28.9	32.9	5.6	5.6	0.0	1.3	2.9	3.5	79.6	4.3	8.6	173.1
Lower Syrdar'ya	78.3	88.9	26.9	26.9	0.0	2.8	5.5	7.3	186.2	7.4	14.9	445.1
Svr Total	1408.4	238.6	95.3	115.0	43.0	28.4	73.7	43.7	952.5	93.3	208.1	3300.0
Percentage	43	7	3	3	1	1	2	1	29	3	6	100
Aral Total	3851.4	428.6	253.2	231.3	88.7	57.2	179.4	147.5	1699.2	246.9	423.5	7607.0
Percentage	51	6	3	3	1	1	2	2	22	3	6	100

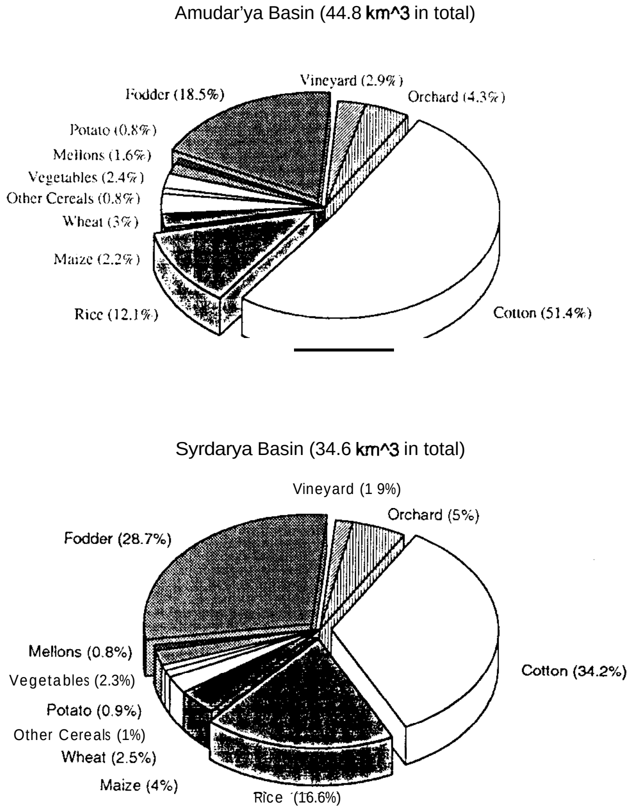

Figure 4. 1987 agricultural water demand shares.

rectifying the water situation in the Aral region are coupled to strategies for cotton: how much, what type, what technologies? Fodder crops account for the second largest requirement, at 29 per cent and 19 per cent of agricultural water demands in the Amudar'ya and Syrdar'ya basins, respectively, It is also notable that water-intensive rice production accounts for 19 per cent and 12 per cent, respectively, of agriculture water demands. The demands for agriculture are built up at the distribution level by multiplying irrigation areas by water application rates [12]. Estimated on-farm water application rates are included in Table 3. These figures are comparable to U.S. rates. In Arizona, where the climatic conditions are similar to the Aral region, the on-farm annual water application rates are of the same order of magnitude: 14,000 m^3 for cotton, 9,000 m^3 for corn, and 12,000 m^3 for potatoes [13].

Water demands for industry (Table 1) are far less than for agriculture, approximately 6 per cent in Amudar'ya and 12 per cent in Syrdar'ya. Depending on economic development strategies in the future,

Water demands for industry . . . are far less than for agriculture

industrial demands may become more significant with time. Industrial demands are built up at the distribution system level from estimates of production output and water use rates. Industrial water demands are currently dominated by the electric power sector.

Municipal water demands comprise about 6 per cent of total demand in the Aral region, as estimated from population and water use data at the administrative district level and allocated to distribution systems. The final two water demand sectors are Livestock and Fishery. As reported in Table 1, known water demands for livestock are quite small, while fisheries account for some 3 per cent of overall water demands.

These water demands discussed above are for final use. They represent the water required by the final user for crop growth, industrial processes, domestic consumption, and so on. To convert these final demands to the actual water supply requirements, WEAP allows for three adjustments to water demands. The first adjustment takes into account the *distribution losses* in each distribution system. For an irrigation system, a considerable amount of water delivered to the field will not be used by the crop root zone due to field evaporation and deep percolation. The second adjustment accounts for water *recycling* or reuse. This refers to processes by which water may be used in more than one application before discharge. For example, irrigation water may be routed for reuse in more than one field. The effect of recycling is to reduce the water required from primary water sources. The third adjustment is for water *transmission loss.* This refers to the evaporative and infiltration losses of water in the canals and conduits carrying the water to a distribution system. Unfortunately, at this stage, our data are insufficient to distinguish the distribution losses from transmission losses, and these two factors are combined in the current estimates. The total withdrawal requirements in the two basins in 1987 were estimated as 127 km^3 (70 km^3 for Amudar'ya and 57 km^3 for Syrdar'ya), or 130 per cent of the estimated final demand.

1987 *Water Supply*

Major surface and groundwater sources are identified in Figs. 2 and 3. In WEAP, surface water is tracked from the flows entering the system through various river nodes. Stream virgin flow data of 1987, which was a wet year for the Aral region, is collected in Table 4 [14]. The total surface water resources in the region comprised 132 km^3, of which 84 km^3 were from the Amudar'ya basin, and 48 km^3 from the Syrdar'ya basin. The 1987 virgin flow figures of Amudar'ya and Syrdar'ya are equivalent to four times and 2.3 times, respectively, the average virgin flow of the Colorado River. On average, the annual surface

Table 3. 1987 On-Farm Water Application Rates (Unit: m3/ha/yr).

	Cotton	Rice	Other Cereals	Potato & Vegetables	Melons	Fodder	Vineyard	Orchards
Amudar'ya Basin								
Pyandz	8700	24900	7200	11600	5600	11400	7330	8530
Vahsh	8700	24900	7200	11600	4900	11400	7330	8530
Kafimigan	9900	26800	8200	13200	6200	12900	8230	9630
Surh-Sherabad	8200	27900	7000	10500	5800	10300	7610	8510
Kashkadraya-Karshi	9100	30800	8300	11700	7000	11300	8070	9070
Bukhara-Zerafshan	10100	32400	9100	12800	7400	12500	8960	9960
Cardzou	10100	32400	9100	12800	7400	12500	8960	9960
Karakum	10600	33400	9200	13500	7500	13300	9590	10790
Horezm	8300	29200	7900	10500	6200	10300	7330	8230
Tashaus	8300	29200	7900	10500	6200	10300	7330	8230
KKAR	7500	28000	7600	9600	5800	9500	6540	7440
Syrdar'ya Basin								
High Narin	7400	22700	7700	9900	5500	9700	6300	8400
Fergana Valley	8500	24800	7700	11400	6000	11200	7100	8400
Middle Syrdar'ya	8700	29700	8100	11000	6800	10800	7770	8670
CHAKIR	8500	24800	7700	11400	6000	11200	7100	8400
ARTUR	7400	27900	7200	9500	5700	9400	6640	7440
Lower Syrdar'ya	7500	26700	7400	8900	5600	8800	6240	6940

Table 4. 1987 Surface Water Sources of the Aral Region (Unit: million m^3).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sent.	Oct.	Nov.	Dec.	Year
Syrdar'ya Basin													
Toktogal res.	313	290	375	467	1457	2514	3134	1861	832	611	500	442	12797
Karasu left	16	12	13	18	48	65	83	70	49	40	31	24	470
Karasu right	45	54	72	256	415	335	213	123	83	76	76	60	1809
Shaydansay	2	2	7	17	22	16	13	11	5	5	6	5	112
Karadarya trib.	191	215	554	1325	2086	2190	1814	1039	468	446	522	436	11284
Kassansay res.	4	5	5	15	69	77	53	28	12	10	11	6	301
Abshirsay	0	0	0	0	67	75	51	27	11	12	8	0	284
Kurvasay		27		26	54	0	0	0	0	0	52		0
Isfayramsay	29		27		21	119	201	153	78	59	26	46	869
Shahimardan	13	7	8	10		41	67	54	34	27		21	335
Isfarasfara	11	24	24	31	24	62	123	137	52	24	54	16	490
sokh	32			81	75	194	375	412	171	75	38	43	1512
Right tributaries	13	12	22		207	220	167	152	93	41		30	1077
Aksu total	16	16	15	17	20	34	52	32	20	24	19	15	281
Kattasay	0	0	0	0	0	0	5	0	2	0	0	5	0
Sanzar	3	2	5	16	16	4	6	3	5	3	5	3	72
Shirinsay	3	3	4	3	3	2617		6	817	4	4		48
CHAKIR total	266	259	446	1098	2160		2312	1646		519	424	377	12941
Aris and Bugun	172	136	208	449	391	361	309	210	125	107	96	95	2658
Lower Syrdar'ya	56	41	89	145	61	16	15	10	7	9	6	8	464
Syr Total	1193	1120	1889	3997	7197	8949	8993	5972	2863	2091	1898	1641	47803
Amudar'ya Basin													
Vahsh	4 5 8	414	597	1143	2137	3603	4446	4178	2136	1117	798	637	21665
Pyandz	1079	975	2036	2929	3884	5780	6803	5544	3525	2119	1674	1253	37602
Kunduz	122	127	149	272	350	638	616	513	290	193	140	125	3535
Kafimigan trib.	166	173	561	998	1413	1463	1109	693	349	339	266	"213	7741
Surhan and Sherabad	90	93	321	691	996	1010	610	384	168	159	137	100	4759
Murgab	75	60	137	231	182	140	59	40	65	88	88	99	1264
Tedjen	0	0	19	137	27	9	0	0	0	0	0	0	191
Artek	13	8	21	57	7	4	3	23	0	22	24	29	212
Kashkadraya	33	36	160	265	236	250	191	103	55	38	35	30	1431
Guzadarya	3	2	17	67	33	29	16	6	6	9	8	7	203
Zerafshan	118	95	178	237	426	984	1298	1158	560	287	211	163	5716
Amu Total	2157	1983	4195	7027	9692	13908	15152	12643	7153	4372	3380	2658	84320
Aral Total	3350	3103	6084	11024	16889	22857	24145	18615	10016	6463	5278	4299	132123

water resources of the Aral region account for some 120 km^3 [15].

As seen in Table 5, the region's groundwater withdrawal in 1987 accounted for 12.3 km^3, 4 km^3 in the Amudar'ya basin and 8.3 km^3 in the Syrdar'ya basin. Evaluating the role of ground water in the region's water budget is complex and, due to limited data, detailed physical interactions between surface water and groundwater are not included at the current stage. Groundwater patterns need more clarification in future analysis.

Water losses on river sections from evaporation and infiltration and returned water from demand sites are taken into account in WEAP. Reservoir water storage and release are simulated by user-defined operating rules. Characteristics of the main reservoirs in the region are summarized in Table 6 [16-18].

PROJECI'IONS

An important concept of WEAP is the distinction between a "business-as-usual" scenario and alternative policy scenarios. The "business-as-usual" scenario incorporates currently identifiable trends in economic and demographic development, water supply availability, water use efficiency, water pricing policy, and other aspects. No new water conservation measures or supply projects are included in the "business-as-usual" scenario. The "business-as-usual" analysis provides a reference against which the effects of alternative policy scenarios may be assessed.

Water Demand Projection

In the past three decades there have been tremendous efforts in water demand projections [19-22]. In general, water demand forecasting approaches fall into four broad categories, each with advantages and limitations: time extrapolation, single coefficient methods, multiple coefficient methods, and probabilistic analysis.

Table 5. 1987 Groundwater Sources of the Aral Region (Unit: million m^3).

Syrdar'ya Basin	
High Narin	1000
Fergana Valley	4800
Middle Syrdar'ya	1000
CHAKIR	1000
ARTUR	250
Lower Syrdar'ya	250
Syr Total	8300
Amudar'ya Basin	
Pyandz	173
Vahsh	275
Kafimigan	459
Surhandarya	416
Kashkadarya & Karshi	299
Zerafshan & Buhara	1030
Cardzou	414
Karakum	591
Lower Amudarya	343
Amu Total	4000
Aral Total	12300

WEAP provides a flexible and detailed structure for water demand forecasting. It is designed to allow the inclusion of a full array of possible demand-side measures. A multiple-level structure is used in WEAP to manage demand data: Sector, Subsector, End-use, Device, and Use-rate. For example, under the agriculture sector, irrigation areas for each crop are defined at the ***Subsector*** level; fractions of irrigation area in each subregion are measured at the ***End-use*** level; irrigation techniques used in each subregion are identified at the ***Device*** level; and water use rates are defined at the bottom level. At each level, activities can be driven by user-specified development targets.

The full complexity of the WEAP demand forecasting structure is being used to develop a range of policy scenarios for the Aral region. However, the rapidly changing political and economic situation in these Central Asian republics — and limited sources of credible data — hamper our exercises. In this paper our task is more straightforward: to introduce the current water accounts and a "business-as-usual" reference projection based on the continuation of current patterns. For the latter purpose, we rely primarily on population growth as demand driving variable. These results provide a benchmark for the more complex policy-oriented demand scenarios.

Hydrological Fluctuations

Hydrological fluctuation patterns are important in estimating future water availability. WEAP is designed to incorporate historic fluctuations to represent future patterns. However, time series data for many elements of the Aral basin are not available. River flows have been altered with the extensive irrigation development and many hydrological records cannot serve as proxies for historic hydrological patterns. Therefore, while WEAP is designed to utilize historic time series data for the general cases, a second, simpler option has also been built into the model for the Aral Sea case.

In the simpler method, five categorizes of water-type years, ***Very Wet, Wet, Normal, Dry,*** and ***Very Dry, are*** used to represent hydrological patterns. These five water-type years correspond to different hydro-

Many hydrological records cannot serve as proxies for historic hydrological patterns

Table 6. Characteristics of Selected Reservoirs.

Reservoir	River Basin	Year of Construction	Maximum Surface Area (km*)	Maximum Storage (10^6 m^3)	Dead Volume (10^6 m^3)	Evaporation Rate (mm/year)
Aumdar'ya Basin						
Tuyamuyun	Amu-dar'ya	1985	650	7230	2390	2000
Nurek	Vahsh	1975	98	10500	6000	1000
Kattakurgan	Zerafshan	1952/1968	84.5	900	60	2000
South-Surhan	Surhan-dar' ya	1964	64.6	800	240	2000
Chimkurgan	Kashka-dar'ya	1963	49.2	500	50	2000
Pachkamar	Guza-dar'ya	1968	14.2	260	10	2000
Syrdar'ya Basin						
Toktogul	Narin	1974	284	19500	5500	1000
Chardara	Syr-Dar' ya	1965	900	5700	1000	2000
Kayrakkum	Syr-Dar'ya	1956	513	4030	1480	2000
Andigan	Kara-Dar'ya	1980	59	1790	150	2000
Charvak	Chirchik	1970	40.3	1990	300	2000
Ahangaran	Ahangaran	1974	8.1	180	40	2000
Tuyabuguz	Ahangaran	1960	20.7	260	350	2000
CHAKIR rsv.	CHAKIR		69.1	2430	7	2000
Bugun	Bugun	1970	63.5	370	20	2000
Kassansay	Kassansay	1956	11	270	7	2000
Karkidon	Kurvasay	1963	9.5	218	0	2000
Dgizak	Sanzar	1967	12.5	90		2000
Kattasay	Kattasay	1965	2.9	60	0	2000
Nayman	Kirgizata	1966	3.2	39.5	1.5	2000

logical occurrence probabilities in conventional frequency analyses. The frequency analysis of an annual inflow record at a representative river point provides a sequence of water-type years. This sequence may then be adjusted to explore alternative assumptions on future hydrological patterns. From the monthly inflow record at the selected river point, average monthly inflows for each water-type year are calculated and the ratios of monthly fluctuations for the four nonnormal years to the normal year are then computed. For every supply source, the base year (the first year in the planning period) monthly inflows are input as data, while values for the future year monthly inflowsare set by the water-type sequence by applying appropriate monthly fluctuation coefficients to the base year inflows.

In this study, monthly inflow data of 1950-1982 at the Tupolang (on Amudar'ya River) and the Narin (on Syrdar'ya River) gauging stations were used in estimating the two basins' water-type sequences during the 19882020 period. Through frequency analyses, the five water-types, Very wet, Wet, Normal, Dry, and Very Dry defined in this study, correspond, respectively, to occurrence probabilities of 0- 1 0%, 1 0-30%, 30-75%, 75-95%, and 95-100%. Because many smaller tributaries don't have time series data, we can only assume that the two defined sequences are reasonable approximations for the entire Amudar'ya and Syrdar'ya basins. Though this method assumes hydrological homogeneity across each of the two basins, it reduces the requirements for historical data while permitting explorations of future water patterns that deviate from historical patterns due, for example, to climate alternations.

Simulation Results

Like other streamflow simulation models, the principle of mass balance guides the water flows through the system in WEAP [23-26]. At each river node, the incoming water is balanced by the outgoing water plus the retained water at the node. Outgoing water is the water diverted, either for demands or other purposes, plus the flow conveyed downstream. Between nodes, evaporation from the stream surface, interaction with groundwater aquifer, and return flows from distribution systems affect the water balance. Each system element, such as a reservoir, has a defined governing rule in passing, releasing, and allocating water. Unlike these models, however, WEAP addresses both the supply and demand issues in an integrated fashion. Demands drive the water allocations among supply sources and demand sites. Detailed demand management strategies as well as the full range of supply development options are incorporated in the model. WEAP provides optional water allocation schemes, one based on priorities and another based on equitable allocation, and flexible reports in various tabular and graphic forms [6].

Table 7 presents the annual average water demand coverage — the ratio of supply available to demand — at each demand site in selected future years. When the coverage value is one, the demand is fully supplied; otherwise, only the indicated portion of the demand

Table 7. Projected Demand Coverage in Selected Years.

	1987	1995	2000	2010	2020
Amudar'ya Basin	Very Wet	Very Dry	Normal	Normal	Normal
Pyandz	1.00	1.00	1.00	1.00	1.00
Vahsh	1.00	0.97	1.00	0.99	1.00
Kafimigan	1.00	0.84	0.96	0.95	0.94
Surh-Sherabad	1.00	1.00	1.00	1.00	1.00
Afghanistan	1.00	1.00	1.00	1.00	1.00
Karakum	1.00	0.94	1.00	1.00	1.00
Kashkadraya	1.00	0.81	1.00	1.00	1.00
Bukhara-Zerafshan	1.00	0.52	0.95	0.94	0.93
Cardzou	1.00	0.31	0.96	0.90	0.89
Lower Amudar'ya	0.99	0.11	0.62	0.61	0.62
Syrdar'ya Basin	Wet	Very Dry	Normal	Very Dry	Dry
High Narin	1.00	1.00	1.00	0.66	0.74
Fergana Valley	1.00	0.88	1.00	0.85	0.91
Middle Syrdar'ya	1.00	0.76	0.88	0.60	0.64
CHAKIR	0.98	0.76	0.94	0.57	0.69
ARTUR	1.00	0.81	0.99	0.74	0.84
Lower Syrdar'ya	0.77	0.30	0.44	0.25	0.22

is met. Coverage is less than or equal to one, since supplies are driven by demands in the model and redundant water is not sent from supply sources to distribution systems.

In the Amudar'ya basin, upstream distribution systems would be mostly satisfied in the selected years, while downstream areas after Kashkadar'ya canal (Fig. 2) such as Bukhara-Zerafshan and Cardzou would face water shortages. In the assumed Very Dry year of 1995, only 3 1 per cent of Cardzou's demand and 52 per cent of Bukhara-Zerafshan's demand could be met. For the Lower Amudar'ya, users could only expect to get 11 per cent of required water in the Very Dry year and about 61 per cent of supply in the ***Normal*** years. For the Syrdar'ya basin, the situation would be more serious than for the Amudar'ya basin. During the Very Dry and Dry years, water supply shortages would occur in almost every distribution system. The Lower Syrdar'ya users, even in the Wet year of 1987, could not fully satisfy their water requirements. They could only satisfy 44 per cent supplies during the ***Normal*** years and no more than 30 per cent supplies during the Dry and Very ***Dry*** years. The shortages for downstream users may be alleviated to a small degree if upstream users are forced to reduce their withdrawals, but this would only spread the unmet demand problem with the overall water shortage situation remaining. While water allocation in the region has been a source of contention since 1980s these projections suggest that the problems, if current patterns are allowed to persist, will only deepen. Withdrawal treaties between the upstream and downstream users along the two river basins, similar to the Colorado River Compact, are urgently needed in the near future.

The simulated annual stream flows entering the Aral Sea from the two rivers are displayed in Table 8. The Aral Sea inflow is projected to average 3.32 km^3 from 1990 to 2000,2.99 km^3 from 2000 to 2010, and 2.54 km^3 from 2010 to 2020, a continuing downward trend. When looking at monthly stream flows in drier years, as in Fig. 5, the seriousness of the situation is underscored. There would be two extremely low-flow periods, January-March and June-September, during which no stream flow would enter the Aral Sea. In a drier year, there would be almost 6 consecutive dry months. As can be seen from the figure, most of the annual stream flow would reach the Aral Sea in spring, with little during the summer seasons. These undesirable patterns suggest that better system operation is needed for the region's water storage and regulating facilities.

By applying these projected stream flows to the Aral Sea, we have calculated the water budgets of the Sea and simulated the future changes of water level and surface area of the Aral (Fig. 6). The Aral Sea's surface area would decrease from its 1987 level of 40.78 km^2 to 9.41 km^2 in 2015, while its water level would drop from 40 meters to 26.8 meters. It is clear that without any action to reduce the demands or to increase the supplies in the future, the sea would continue to shrink at roughly the same rate as it did in the 1980s devolving into one or several residual brine lakes.

DIRECTIONS FOR POLICY SCENARIOS

One of the primary objectives of our study is to examine alternative future development scenarios for the Aral region. Using the "business-as-usual" projections as a point of departure, the next step in the project involves the creation of a number of ***policy scenarios,*** or alternative water futures incorporating a wide range of possible measures that alter "business-

Table 8. Projected Yearly Flows Entering the Aral Sea (Unit: km^3).

	Amudar'ya Water-type	Flow to Aral	Syrdar'ya Water-type	Flow to Aral	Total to Aral
1987	Very Wet	6.28	Wet	2.51	8.79
1988	Normal	1.96	Normal	1.18	3.14
1989	Normal	1.89	Normal	1.14	3.03
1990	Normal	1.88	Very Wet	2.13	4.01
1991	Wet	2.53	Normal	1.17	3.70
1992	Very Wet	3.51	Normal	1.13	4.64
1993	Normal	1.93	Wet	1.19	3.12
1994	Normal	1.87	Very Wet	2.38	4.25
1995	Very Dry	0.69	Very Dry	1.23	1.92
1996	Normal	1.86	Dry	0.91	2.77
1997	Normal	1.85	Normal	1.07	2.92
1998	Normal	1.85	Normal	1.09	2.94
1999	Normal	1.84	Normal	1.08	2.92
2000	Normal	1.84	Normal	1.08	2.92
2001	Normal	1.83	Normal	1.07	2.90
2002	Very Wet	3.36	Wet	1.13	4.49
2003	Normal	1.87	Normal	1.13	3.00
2004	Normal	1.82	Wet	1.17	2.99
2005	Dry	1.09	Dry	0.97	2.06
2006	Wet	2.45	Normal	1.05	3.50
2007	Normal	1.81	Wet	1.12	2.93
2008	Normal	1.80	Normal	1.12	2.92
2009	Dry	1.06	Normal	1.08	2.14
2010	Normal	1.79	Very Dry	Q.83	2.62
2011	Very Wet	3.26	Normal	0.50	3.76
2012	Dry	1.06	Dry	0.89	1.95
2013	Dry	1.04	Dry	0.18	1.22
2014	Normal	1.78	Dry	0.17	1.95
2015	Dry	1.03	Wet	0.57	1.60
2016	Wet	2.39	Normal	1.10	3.49
2017	Wet	2.38	Normal	1.04	3.42
2018	Normal	1.76	Normal	1.04	2.80
2019	Wet	2.37	Dry	0.88	3.25
2020	Normal	1.75	Dry	0.16	1.91

as-usual" projections. Policy scenarios will include actions in three areas: changing demand patterns through efficiency .improvement and economic re-orientation, better managing the existing system and developing new local water sources. Each of these categories of intervention encompass many separate measures, such as pricing policies, investment strategies, and technological and operational options. For example, irrigation efficiency can in principle be improved through various technologies (sprinkler, drip, or trickle systems), through improved water application scheduling or through land leveling and contouring.The feasibility of any or all of these in the Aral region is being studied in detail.

It is' noted that our study has focused on the potential for local solutions to address the problems of the region. ,Nonlocal water supply enhancements considered in the past include artificially increasing rainfall, increasing the rate of glacial melting, transferring Caspian Sea water and transferring Siberian river water. Each of these proposals has met with great concern about environmental impacts. Moreover, critics of the most advanced of these proposals, the north-south Siberian water transfer, have raised questions about the cost-effectiveness of such a large-scale project, the politics of inter-republic resource transfers and the impacts on local cultures. The project is currently suspended.

These exercises provide a laboratory for experimenting with alternative futures

We anticipate many alternative scenarios, each evaluated on economic and environmental criteria. The scenarios will begin with the ***business-as-usual scenario*** reported here that quantifies the degree of water shortages over time, the increasing pressure on the lake, and the scale of required remedial efforts and go on to an ***Aral Sea stabilization scenario*** (just stabilizing the sea requires significant improvements in today's water-use efficiency and local supplies); and an ***Aral Sea restoration scenario*** requiring radical changes in the future water and economic strategy for the area in order to return inflow above equilibrium levels. In each case, the feasibility and costs will be assessed.

These exercises provide a laboratory for experimenting with alternative futures for the Aral Sea region. It is hoped that such glimpses of the future will help steer current policies in a sustainable direction.

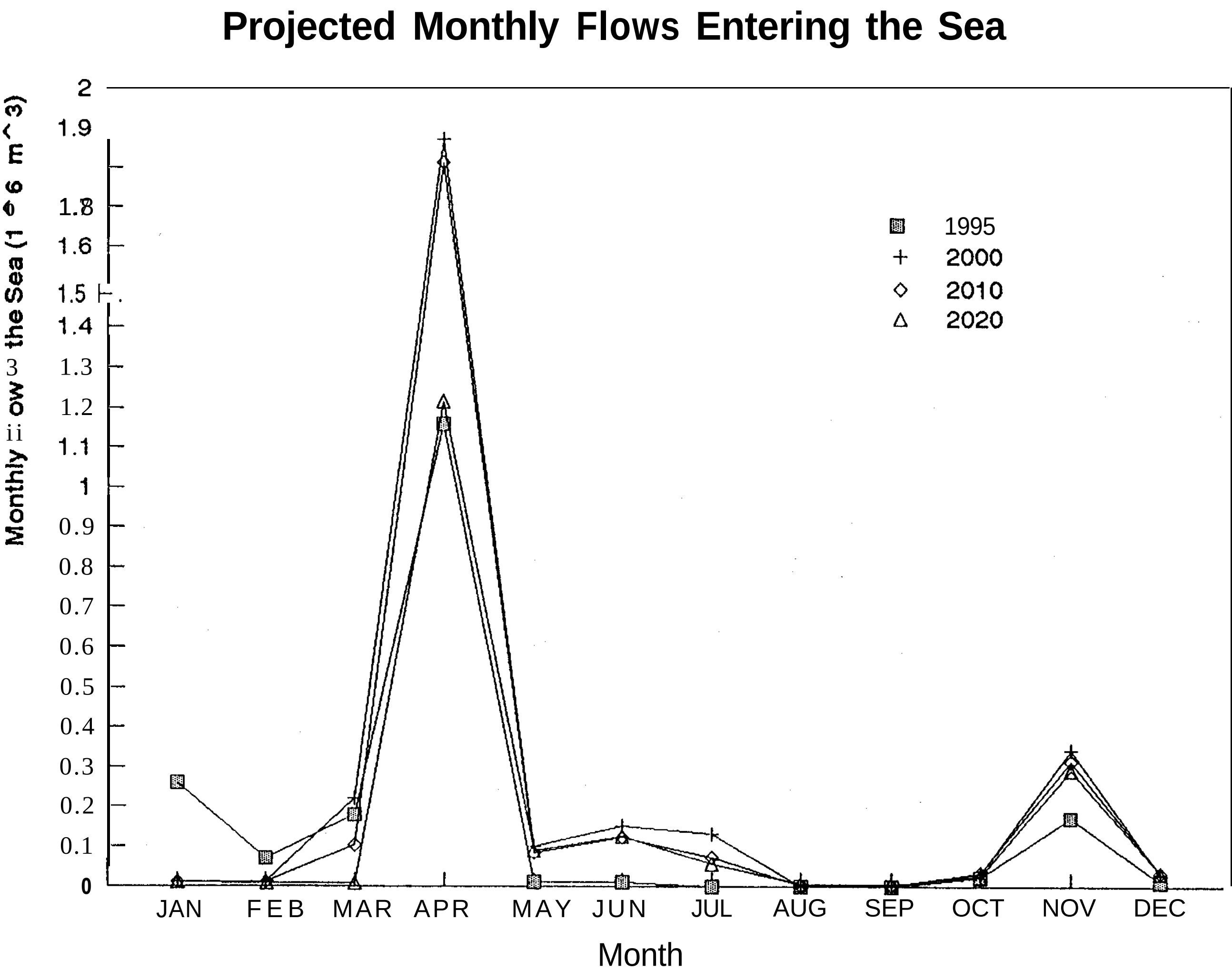

Figure 5. Projected monthly flows entering the Aral Sea.

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Aral Sea Projections in Businks-as-usual Case

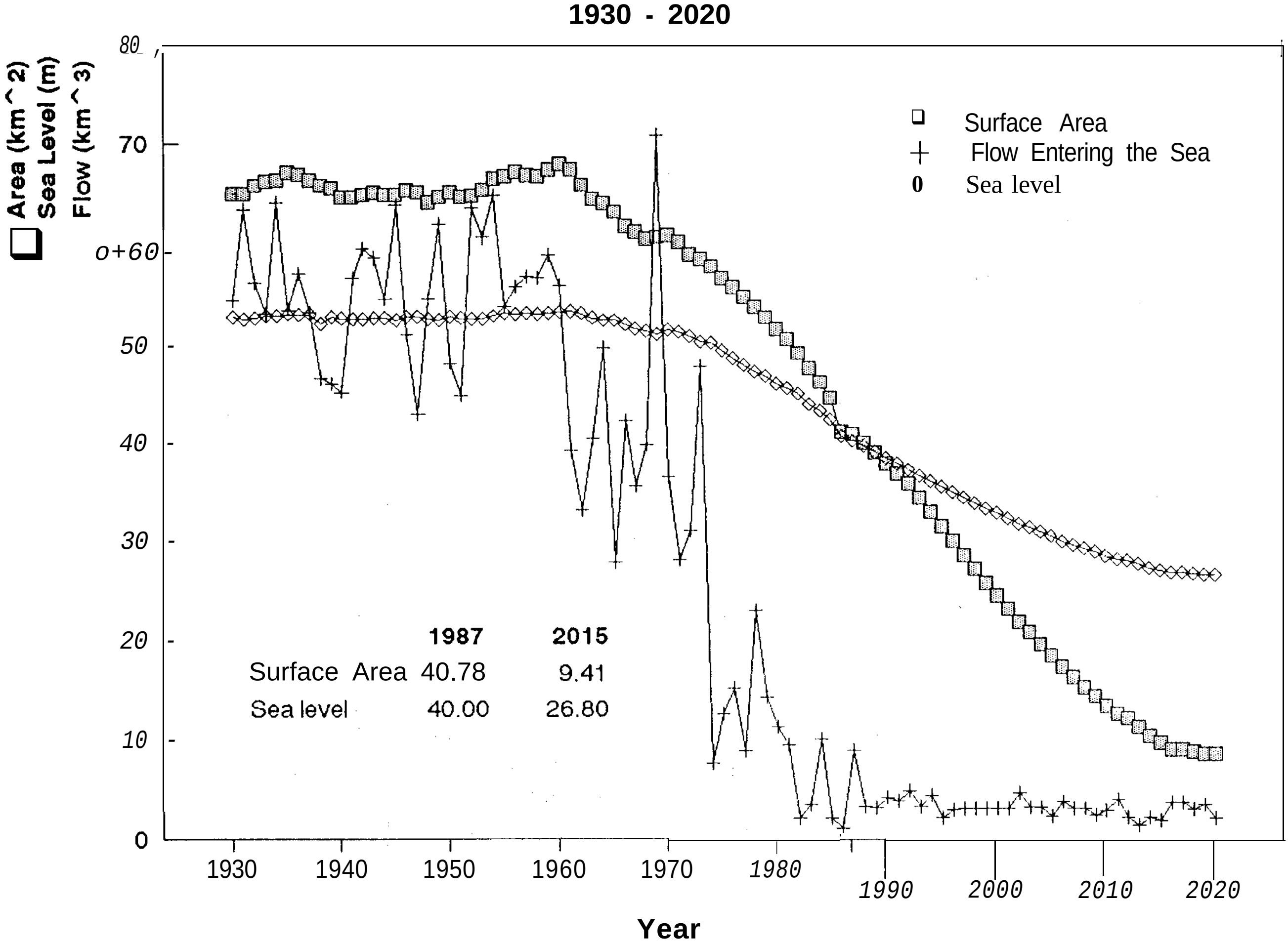

Figure 6. **Base case projection for the Aral Sea.**

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